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Radio Astronomy for the VHF/UHF Radio Amateur

Based on a Lecture given at the 1988 VHF/UHF Conference in Munich

There is hardly a radio amateur who is not acquainted with pictures of the huge astronomical radio telescopes. These range from the 100 m mirror of the Max-Planck institute at Effelsberg in Germany to the 300 m (approx.) Arecibo telescope located in a natural depression in Puerto Rico, to name only two of the biggest.

One has heard of the fantastic receivers employed using super-cooled pre-amplifiers, of the computers for antenna control and filtering the signal from the basic intrinsic noise generated by the receiving system. Radio signals from other stars, the interstellar material or signals from other galaxies, are received by these systems. Signals which have travelled for millions of years before they have impinged upon the Earth's surface.

One hears about the discovery of strange objects, of Quasars and Pulsars, burned-out stars and the discovery of carbon-dioxide molecules even in distant neighboring galaxies. A fantastic world of the universe as seen with the radio eye (1).

Only a few radio amateurs know, however, that they can also delve into this fascinating world, using their own equipment, even if the last named wonders will be denied them. But there is – apart from the Sun – a few further intra and extra-galactical signal sources whose radiations are sufficiently intense to be observed by amateur means. The purpose of this article is to explain how this may be achieved. It will acquaint those interested with a few basic considerations and present him with some assessments and evaluations. These will assist in the decision of whether, or not, a further incursion into this area, is interesting enough to merit the trouble and expense.

1. HISTORICAL

It all started about 50 years ago when Karl Jansky, a radio engineer at the Bell laboratories in Holmdel, New Jersey, USA, was examining the interference to radio reception near the present-day 15 m band. His array comprised four two-element Quad antennas (2) rotatable in both the azimuth and horizontal planes. He found three natural interferences sources. These were distant and local thunderstorms and a constant noise which intensified when he directed his antenna towards Orion "The Hunter" constellation near the centre of the Milky Way. He was thus the first person to recognize radio emissions which originated from space even though it as in quite

a co-incidental manner. The (optical) astronomers, however, displayed little interest, at first, in the fact that a new window had been opened to the universe which could be used to explore its wonders.

Interest was shown by an amateur astronomer, Grote Reber in Illinois, who was exited by Jansky's discovery. He constructed a 10 m parabolic mirror in the garden of his house and began to systematically search the heavens. At first, he had no success when he tried at 3.3 GHz and at 910 MHz but he heard what he was searching for on 160 MHz.

In 1944, he published the first radio map of the heavens i.e. as "seen" by a 160 MHz receiver. He found the strongest radio sources in Cassiopeia A, Cygnus A, Sagittarius etc in an almost continuously radiating celestial dome. The 160 MHz antenna had a beamwidth of approximately 12° which limited the detail on his map but the resolution was good enough to be able to identify individual objects.

Following the war, the young science was able to procure electronic equipment intended for military purposes and thereby received a tremendous fillip. This material included radar installations (Würzburg Giant etc.) and, of course, skilled radar technicians who made their experience available. The greatest activity in these post-war years was aroused in England and Australia but many more countries later developed experimental installations.

Two important discoveries in the rich history of Radio Astronomy should now be mentioned.

In 1951, the emission of galactic hydrogen, predicted in 1944, was discovered at a frequency of 1420.4056 MHz and whose spectral analysis led to the realization of the spiral nature of our own galaxy (3). Also, in 1964, workers at the Bell Laboratories using a sensitive receiver and a gigantic antenna installation at 7.3 cm, discovered the cosmic 2.7 K background, or residual radiation, whose existence tended to confirm, to a very high degree, the bigbang theory of the origin of the universe. The installation was only 3 km from the place where Jansky made his pioneering discoveries.

It should not be left unsaid, that when Jansky's original equipment was used 15 years later to try and emulate his findings, nothing could be heard. Unfortunately, the interference level in the band he was using had grown to such proportions that the radiations from the Milky Way were completely obscured.

2. RADIO EMISSIONS

Radio emissions, such as those which may be received from space, have the random character of noise in a resistor or from an amplifier. It is, in general, wideband inasmuch that it can be observed over all the frequencies familiar to amateurs i.e. 20 to 20,000 MHz. Its special frequency characteristic, however, betrays something of its origins. Three mechanisms come into play here. The radiation from a black body, the thermal radiation of an ionized gas and the synchrotron radiation.

Every body having a finite temperature, emits electro-magnetic radiations over a large radio-frequency spectrum. "Continuous radiation" is spoken of as opposed to "linear radiation" by which the emissions are radiated on one or several discrete frequencies. If the body is ideally black, i.e. it absorbs all the energy at all wavelengths, then its emissions, or more exactly, its spectral energy density, may be found by means of a well-known formula. This complicated formula was evolved by Max Planck at the beginning of this century. This quantifies the rule, that the hotter the body is the stronger are its emissions in all parts of the spectrum. That spectrum has a particular maximum, which, with rising body temperature is shifted into the short-wave regions. The emission-maximum of a body at room temperature, 300 K, lies in the infrared spectrum. If the body is cooled to the region of a few degrees Kelvin the emission maximizes in the millimetre band. The Sun too, behaves almost as a black radiator over the whole frequency spectrum with the emission maximum occurring in the green-yellow spectrum i.e. 0.5 μm. From

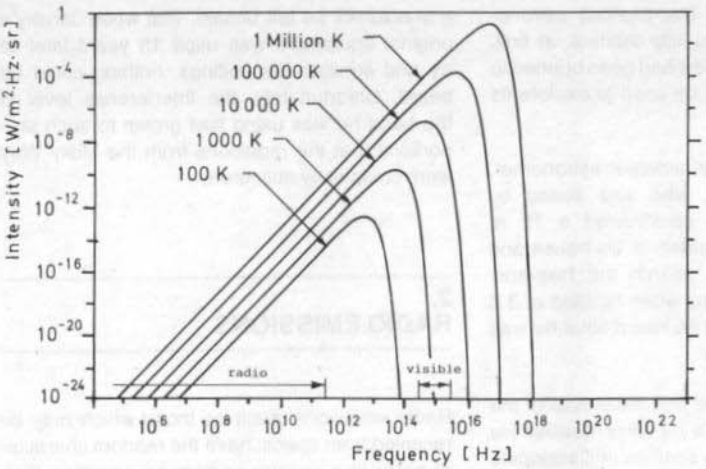

Fig. 1:
Black-body spectrum at various radiator temperatures

this information, the surface temperature of the Sun's photosphere may be calculated to be about 5800 K.

As shown in **fig. 1**, the radiation maximum for the given temperature parameter takes place at shorter wavelengths than those belonging to the classical radio spectrum. The total radio wave spectrum lies in the rising, linear portion of the individual characteristic. In this part of the emission spectrum, the Rayleigh-Jeans law is used to describe the classical Planck law for the long-wave emission spectrum. The specific intensity I_λ of the black body can then be given for a polarization direction by: –

$$I_\lambda = \frac{k\,T}{\lambda^2} \quad (W/m^2 \times Hz \times rads) \qquad (1)$$

where T = the absolute temperature of the body
λ = wavelength
k = Boltzmann's constant =
$= 1.38 \times 10^{-23}$ J/K

If this is then multiplied by the space angle Ω_Q, under which the source under observation appears, the flux S, given in Watts per square metre and per Herz bandwidth, can be obtained.

As the radiation flux of radio-astronomic sources is very small, a flux unit of 10^{-26} W/m² Hz has been chosen in honour of the radio astronomer Jansky and is shorted to the "Jy".

The equation (1) is only valid for the case of the ideal black radiating body. The equation is used for the definition of an equivalent radiation temperature whereby an observed flux from any non-ideal, or from the superimposition of several radiators, will result in the same flux as that calculated from an equivalent black radiator temperature according to eq. 1.

Whilst most bodies in the solar system are thermal radiators, many sources display quite a different dependence from that typical of a black body radiator. Quite a different mechanism is clearly the reason. One example of this, is the Synchrotron radiation of high energy electrons which leads to a linear emission relationship with wavelength. To delve further into the various mechanisms would be quite inappropriate for an article of this scope. **Fig. 2** gives examples of the frequency dependence of the flux of a few sources.

Besides these continuous radiations, there are linear radiations. The most prominent of these, is

that mentioned in the beginning of the article, namely, the hydrogen line near the 23 cm band. Neutral hydrogen is found in the Galaxy with a density of approximately one atom per cubic centimeter. The expansion of the interstellar space is, however, so great that the total amount of radiation from the depths of space is sufficient to be observable.

From the linear profile, and the frequency shift of this radio line due to the Doppler effect, further important conclusions may be drawn concerning the structure of the Galaxy.

3. DISTRIBUTION PATHS

Whilst the greatest obstacle for optical observations is the absorption of the light rays by the interstellar dust particles and, of course, the Earth's atmospheric conditions, the strength of astronomical radio signals is determined by both the absorption characteristics of ionosphere and atmosphere. Their characteristics lead to the existence of a radio window, an open portion of the spectrum from 1 cm to 10 m (**fig. 3**) which allows the signals to pass through with minimum attenuation.

The long-wave end of this window will be familiar to the radio amateur as being influenced by the ionosphere, whilst the limit of the shorter-wavelength end, in the mm-range, is determined

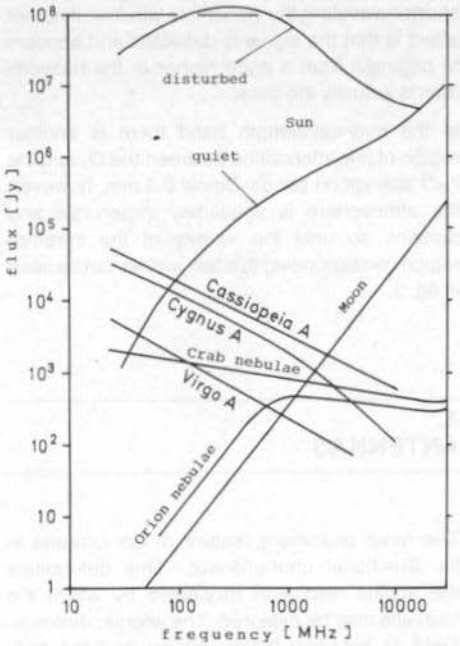

Fig. 2: The flux of the strongest sources as a function of frequency

by absorption of the signals by water (H_2O) and to a lesser extent by other molecules such as oxygen O_2. However, within this window the signal strength can also be affected by a variety of afflictions. Among these, rain and fog make a noticeable effect upon the attenuation of the

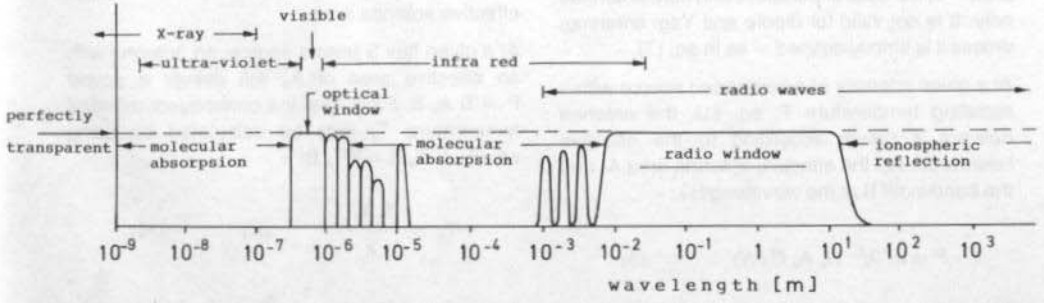

Fig. 3: The total transparency of troposphere and ionosphere

shorter wavelengths within this window. Another effect is that the signal is deflected and appears to originate from a point higher in the heavens than is actually the case.

In the mm-wavelength band there is another region of low attenuation between the O_2 and the H_2O absorption bands. Below 0.3 mm, however, the atmosphere is absolutely impervious and remains so until the vicinity of the infra-red region corresponding to a few μm, as can be seen in fig. 3.

4. ANTENNAS

The most prominent feature of an antenna is its directional characteristic. This determines the spatial resolution properties by which the heavens may be explored. The angular displacement Θ between the maximum and the half-power point on an antenna's polar diagram, is determined by the relationship between the wavelength λ to the paraboloid's diameter D and may be given approximately by: –

$$\Theta = 60\,\lambda/D \text{ (degrees)} \qquad (2)$$

The sensitivity of the antenna as a radiation receiver is described by the effective area of the mirror A_e. This extraordinarily helpful quantity has a direct relationship with the geometrical antenna area – in the case of parabolic and horn antennas only. It is not valid for dipole and Yagi antennas unless it is strictly defined – as in eq. (7).

At a given intensity of an extended source with a radiating temperature T, eq. (1), the antenna delivers a power according to the effective beamwidth Ω_e, the effective antenna area A_e and the bandwidth B at the wavelength λ: –

$$P = kT/\lambda^2 \cdot \Omega_e\, A_e\, B \text{ (W)} \qquad (3)$$

The antenna's effective beamwidth Ω_e is expressed in terms of the beamwidths in both the E-plane $\triangle\Theta$ and the H-plane $\triangle\Phi$ and is given by: –

$$\Omega_e = 4.1 \times 10^{-4}\, \triangle\Theta\, \triangle\Phi \text{ (rad.)}$$

$$\lambda^2 = A_e\, \Omega_e \text{ (m}^2\text{)} \qquad (4)$$

Therefore eq. 3 can be simplified to: –

$$P = kTB \text{ (W)} \qquad (5)$$

An antenna which is "illuminated" by a black body of temperature T and bandwidth B, delivers at its output terminals a power kTB. This power is identical with the noise performance of a resistance which has a temperature T. This fact is used for the absolute calibration of the radiometer system.

A receiver which has been calibrated by this means measures just about the same input power in Kelvin antenna temperature. This has nothing at all to do with the ambient temperature which the antenna is subjected to. It is that temperature which a black body must have to produce the same power at the antenna output terminals. The antenna temperature, when fully illuminated, is then identical with that of the radiator's. In this case, a simple dipole will deliver the same power as a high-gain antenna but, of course, this cannot possibly be the case. Actually, the antenna temperature becomes smaller as the relationship between the antenna beamwidth and the source diminishes (7).

An observation of a source having very small dimensions requires an antenna of low beamwidth, i.e. high gain, which necessitates a large effective antenna area.

At a given flux S from a source, an antenna with an effective area of A_e will deliver a power $P = S\,A_e\,B$. From this, the consequent antenna temperature T_a may be calculated by using eq. (5): $S\,A_e\,B = k\,T_a\,B$: –

$$T_a = \frac{S\,A_e}{k} \text{ (K)} \qquad (6)$$

The strongest sources, Cassiopeia A and Cygnus A have a flux of some 10,000 Jy. Even with an

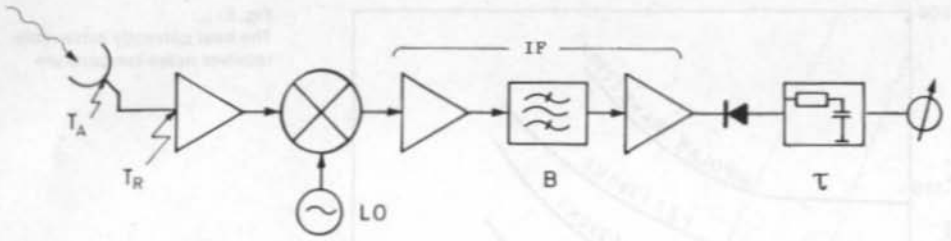

Fig. 4: Block diagram of a typical radiometer

antenna of effective area of only 1.5 m^2 results in an antenna temperature of approximately 10 K. This knowledge, on the face of it, seems to imply little difficulty, but nothing has been mentioned about the effect of interference in the observation frequency band.

EME experiments by radio amateurs give some idea of what the antenna requirements have to be for astronomical purposes. At least the same antenna system as used for amateur astronomy as is used for amateur EME communication: parabolic dishes up to six metres diameter i.e. an effective antenna area of 20 m^2 or a Yagi array with 20 to 24 dB gain would be ideal. The effective antenna area may be arrived at for a Yagi array in the following manner: The gain G is defined from the relationship $G = 4\pi/\Omega_e$, where the gain G is referred to an isotropic radiator. The effective antenna area is then given by: –

$$A_e = \frac{G\lambda^2}{4\pi} \qquad (m^2) \qquad (7)$$

An antenna having a gain of 23 dB (200) has an effective antenna area of $A_e = 7.8\ m^2$ in the 70 cm band.

5. RECEIVER

The most important component part of a radio-astronomy installation is the receiver. Super-heterodyne receivers, familiar to all radio amateurs, are invariably employed (2, 4, 5, 6, 7). The block diagram of **fig. 4** shows such a receiver. In the place of the demodulator a quadratic detector has been employed. This gives a voltage output which is proportional to the noise power input to the receiver (8). The noise power is directly proportional to the bandwidth B of the IF amplifier. An integrating network follows the detector which has a time constant τ. This introduces a time average into the noise power. The averaged signal is then further amplified and taken to a pen recorder.

The noise temperature of the whole system is T_r. The noise power referred to the receiver input is $P_r = k\,T_r\,B$. The bandwidth B should be as large as possible for the observation of continuous sources and consequently the signal power, in accordance with eq. 5, will be accordingly large. An IF bandwidth will be a few MHz wide in the metric bands and up to 100 MHz in the centimetre bands. Assuming that B = 10 MHz and T_r = 100 K, then the total power at the receiver input terminals will be:

$$P_r = k\,T_r\,B = 1.4 \times 10^{-14}\ W,$$
i.e. – 109 dBm approx.

This will be amplified in the receiver to approximately 10^{-5} W, i.e. – 20 dBm approx. at the detector diode. This results in a total voltage gain G_V for the receiver of 90 to 100 dB from antenna input terminals to detector.

An automatic gain control is not fitted to the receiver as the signals under examination are of the same order as the receiving-system's own internally generated noise.

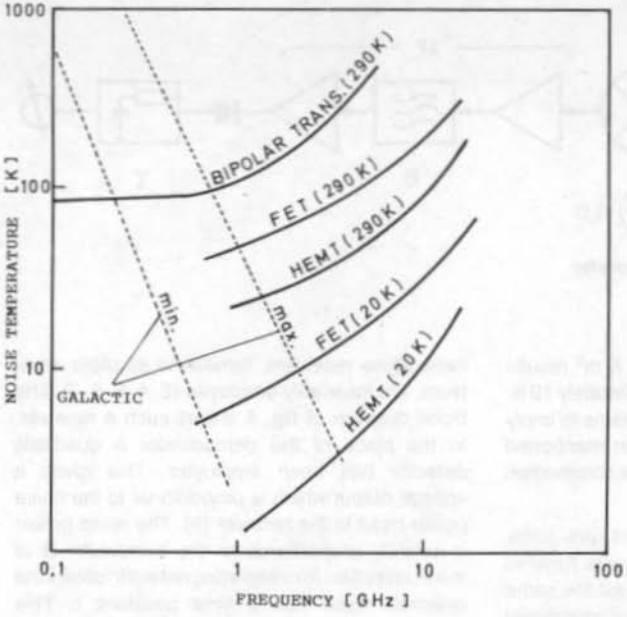

Fig. 5:
The best currently achievable receiver noise-temperature

The wanted cosmic signals are fed, together with the indistinguishable system noise, to the receiver input and having a total power of P_s which stems from the antenna temperature T_a. The total power consisting of the sum of the noise power and the signal power present at the detector diode is then: –

$$P = G_v k B (T_r + T_a) \text{ (W)} \qquad (8)$$

Normally T_a is noticeable smaller than T_r. The object then is to identify a signal which has been buried in the receiver system noise.

Radio communication techniques can normally rely upon the received signal being many times as strong as the average receiver-system noise power. This would be in accordance with the comparison of P_s and P_r in the above case, if the absolute value in the average receiver-system noise power in the astronomical case is not considered, but only their variations. This is why it is meaningful, as the average value of the noise power can be measured and compensated for by the time constant τ of the detector integrator network. The actual unwanted noise are the variations which this DC output signal has impressed upon it. Their magnitude depends, of course, upon the time constant τ but also upon T_r and the IF bandwidth B. The relationship gives rise to the formula given by Dicke which gives the RMS value of the variations T_{min}: –

$$T_{min} = \frac{T_r}{\sqrt{B\tau}} \text{ (K)} \qquad (9)$$

For example; if τ = 10 s, B = 5 MHz, T_r = 100 K then T_{min} = 0.014 K. This means that an antenna temperature $T_a = T_{min}$ can be measured with a signal-to-noise ratio of unity!

For example, say if under these conditions a source having a T_a of 5 K is under observation. The ratio S/R = 354, i.e. when the antenna is directed to this source, the receiver output voltage, the RMS value of the receiver produced system noise, rises by a factor of 354.

In order that the receiver sensitivity can be as large as possible, the IF bandwidth and the

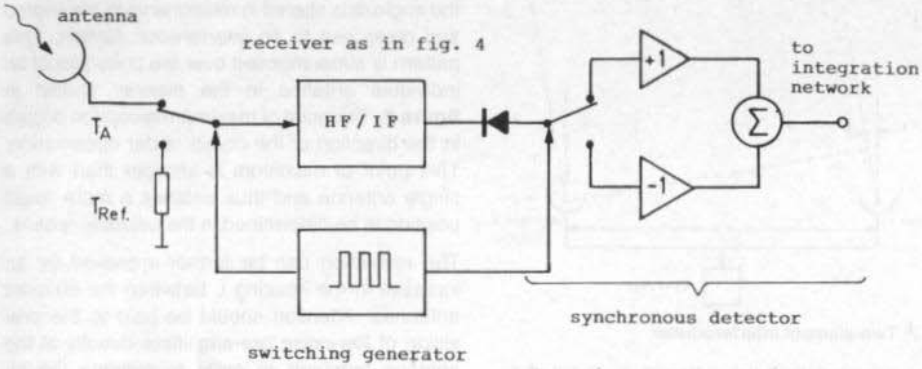

Fig. 6: "Dicke-switch" radiometer

integration time must be as large as possible in accordance with eq. (9). This then ensures that the receiver noise temperature is as small as possible. The methods of ensuring this are familiar to radio amateurs, noise temperatures under 100 K are able to be achieved well into the GHz range by means of GaAs-FET pre-amplifiers.

Unfortunately, the limit sensitivity as indicated by eq. (9) cannot quite be achieved. The cause of this lies in the inconsistency of the overall amplification due to the temperature variations, supply voltage fluctuations and receiver intrinsic noise. In particular, the low-frequency 1/f-component of the total noise, which originates in the active components together with DC drift in the amplification following the integration network, are responsible for a large part of the short-fall in performance.

In 1946, Dicke developed a receiver which went a long way to eliminating these defects. The block diagram is shown in **fig. 6**. This type of receiver switches the receiver input between the antenna and a constant-temperature termination resistor $R_{ref.}$ at a rate of 10 to 100 Hz. In a synchro-detector, the detector output voltages are separated from each other and the two components. Two quantities are measured: receiver noise + antenna signal and then, receiver noise + reference signal. Then they are subtracted from each other. The termination resistor produces the noise power $kT_{ref}B$. The periodic output signal has an amplitude: –

$$U_{pp} = \eta\, G_v\, k\, (T_a - T_{ref.})\ (V) \qquad (10)$$

where η is the diode sensitivity given in V/W.

It can be shown that the gain variations are nullified when T_a is arranged to be equal to $T_{ref.}$.

Even when this calibration is disturbed due to temperature variations in the reference termination, the "Dicke switch" has the advantage of suppressing the DC component to the level of the receiver basic noise. This facilitates linear amplification in the final DC amplifier thereby reducing the 1/f component to zero.

6. INTERFEROMETER

The resolution of a radio telescope can be dramatically improved by employing the interferometer principle. This principle offers the amateur one of the greatest possibilities to improve the system at a low-capital outlay.

The simplest interferometer consists of two identical antennas separated by a distance L in the east-west plane (**fig. 7**). The greatest antenna gain is perpendicular to this plane. The elevation

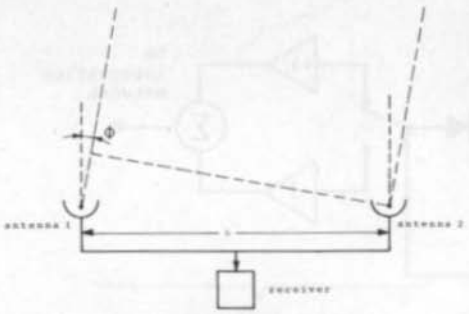

Fig. 7: Two-element interferometer

is so adjusted that the antenna is directed to the source when the latter is in the meridian. The signals from the source are fed to the receiver by two transmission lines of equal length.

A signal arriving at an angle Φ to the plane of the antenna will produce two components with a phase difference of (π L/λ) (sin Φ), where λ is the wavelength at the working frequency. The components at the detector outputs will have an identical phase difference and will add vectorially to produce a voltage U. This is related to the incidence angle Φ by: –

$$U \approx (1 + \cos(2\pi L/\lambda \times \sin \Phi)) \qquad (11)$$

If, owing to diurnal movements, the object under observation passes through the antenna lobe, the angle Φ is altered in relationship to the source and gives rise to an interference pattern. This pattern is superimposed over the polar plot of an individual antenna in the manner shown in **figure 8**. The point of maximum reception occurs in the direction of the object under observation. This point of maximum is sharper than with a single antenna and thus enables a more exact position to be determined in the celestial sphere.

The resolution can be further improved by an increase in the spacing L between the element antennas. Attention should be paid to the provision of low-noise pre-amplifiers directly at the antenna terminals in order to mitigate the increased loss caused by the longer transmission lines. Both pre-amplifiers should have constant group-delays and be identical in all other respects.

The two-element interferometer can be usefully modulated at periodic points in the antenna transmission lines. This is injected by means of a λ/2 line to one antenna, and the modulation also synchronously demodulates the receiver output. The synchrodyne demodulation has the effect of subtracting the elemental patterns of fig. 8, one of which has been delayed by the λ/2 line. The result is that the subtraction yields a minimum in the middle where there was formerly a maximum.

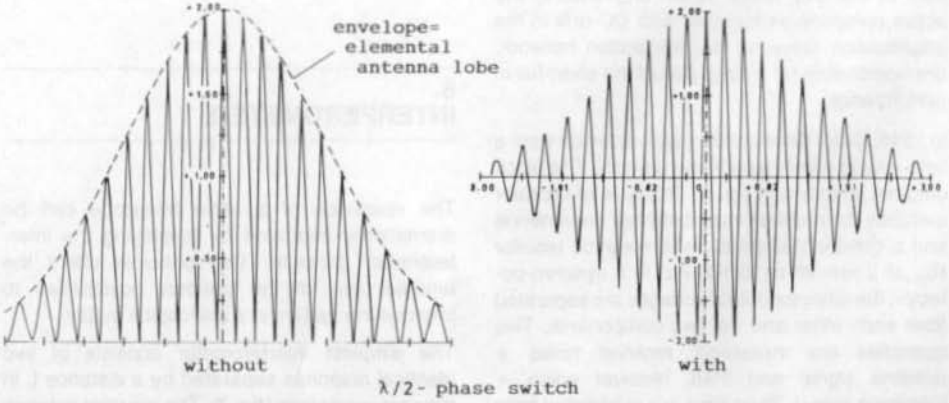

Fig. 8: Two-element interferometer interference pattern

From the foregoing, it will be quite apparent that there will be no great challenges presented to the amateur by the construction of an interferometer. All it requires is, for example, two Yagi arrays comprising 2 to 4 elemental antennas each with 10 dB_d gain, and spaced by a distance of 10 metres. This installation will be sufficient to examine the stronger astronomical radio sources (10).

7. CELESTIAL OBJECTS

The Sun is the strongest source in the whole cosmic radio spectrum (9). Its radiation can largely be separated into four types: the Sun's quiescent radiation, the slowly varying Sun-spot component, the noise storms in the metre-wave range and the large outbreaks of radiation. Above 10 GHz and under 100 MHz the Sun behaves as a black-body radiator. Outbreaks of radiation are largely confined to the metric bands and can increase the Sun's flux by as much as an order, fig. 2.

The radiation from a planet is mainly thermal in nature and in accordance with its surface temperature, about 500 K for the nearest planet to the Sun, Mercury, and approximately 50 K for the outer planets, Neptune, Uranus and Pluto. In the metric-wave region, they are therefore the very weakest of radiators. They only become strong sources in the mm-wave region in accordance with eq. (1).

The same applies to the Moon. Its radiation is shown in fig. 2. The Moon is a prime example of a thermal radiator. Its mean temperature amounts to some 230 K and superimposed upon this are the periodical extremes caused by the Moon's phases. These relationships are so well-known that the Moon can be employed as a system calibration source.

Only the planet Jupiter deviates clearly from a thermal radiator. Its intensive radiation outbreaks in the short-wave range were eluate known in 1955, again, purely by chance. The surface temperature is 130 K in accordance with the radiation temperature measured in the 3 cm waveband. In the 10 cm band, the radiation temperature amounts to approximately 600 K and at 70 cm above 50,000 K. The cause of this evident non-thermic emission is the gyrating movement of fast electrons in the magnetic field of Jupiter. The observed intensive radiation is then a synchrotron radiation.

Table 1 lists the strongest radio sources, after that of the Sun, in the 200 MHz region:

Of the galactic objects, the remnants of super-novae are mainly the stronger radio radiators. The best known is the Crab Nebulae, the name of this source is Taurus A. Another one is Cassiopeia A, the strongest radio source, apart from the Sun, that can be detected upon Earth.

The second strongest radio source is Cygnus A, a galaxy 550 million light-years away. The intensity with which this source emits radio waves is enormous. It exceeds its light emission by many times in power output. Objects possessing these characteristics are known as radio galaxies. Cygnus A is the most prominent representative of over 100 so far known objects of this kind.

Name	Flux (Jy) (200 MHz)	Type
Cassiopeia A	11000	Super-novae remnant
Cygnus A	8100	Galactic
Taurus A (Crab Neb.)	1400	Super-novae remnant
Virgo A	970	Galactic
Sagittarius A	1000	Galactical core

Table 1

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